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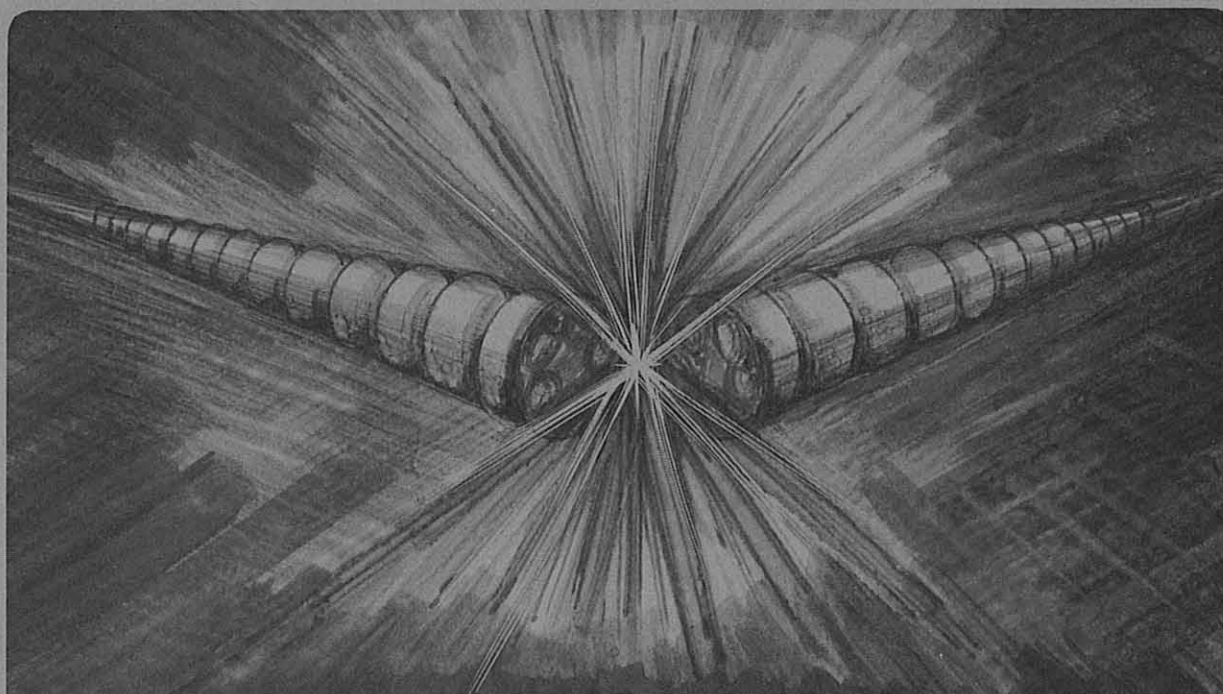
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Transverse Feedback in a 100 TeV Storage Ring

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TRANSVERSE FEEDBACK IN A 100 TeV STORAGE RING*

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TRANSVERSE FEEDBACK IN A 100 TeV STORAGE RING

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Introduction

The general purpose for a transverse feedback system in the proton collider is to stabilize coherent bunch motions and reduce them to a small amplitude that will result in an acceptable diffusion rate into incoherent motion. Strong instabilities are expected to be caused by the resistive-wall impedance of the beam tubes in pulsed magnets at the low revolution frequency. The feedback must stabilize thousands of coupled-bunch modes. It must also damp excursions of the injected beam and suppress excitations from noise in magnetic fields, in support structures, and in the feedback circuits. It may also be important in combating some beam-beam interaction effects. Damping by synchrotron radiation will be important in the long-term evolution of the emittance, but it is too weak to be a factor in the coherent damping.

Design Issues

With ~50,000 bunches in the ring, there are half that number of coupled-bunch modes that may be unstable and one expects many thousands of these to grow under the influence of various narrow-band beam impedances. A broad-spectrum feedback is needed and most suitable would be a bunch-by-bunch method in which the position of each bunch is measured and a correction directed to that same bunch.

The amount of broad-band power required to kick each successive bunch is a measure of the scale of the feedback system and can become of concern if it is required to damp sizable injection errors in a large fraction of the circulating beam.

Feedback gain is not in itself a problem of hardware or of cost, but is limited by the dynamics of the bunch motion if one tries to damp a growth rate $1/\tau$ that approaches the orbital frequency f_0 . A practical limit of $1/\tau < f_0/6$ has been assumed here and would be a machine design parameter affecting particularly the bore tube. With a second feedback system in betatron-phase quadrature or with multiple systems acting over less than a full turn between pickup and kicker one might extend this limit. But in what follows, a single system in each transverse direction having one turn delay will be assumed.

Continual noise excitations of the transverse motion will, with feedback operating, result in a steady-state oscillation amplitude. The contribution of feedback-

circuit noise will be estimated; the strengths of other noise sources are not yet known but the presence of feedback will reduce their effects.

Example Parameters

The parameters of 100-GeV rings, one with low magnetic field and one with strong field, are listed for use in these example feedback calculations.

Parameters for two example rings

2	8	= B [tesla]
10^{35}	10^{35}	= \mathcal{L} [$\text{cm}^{-2}\text{sec}^{-1}$]
219	877	= f_o [Hz] orbital frequency
38	38	= f_B [MHz] bunch rate
10	10	= E [TeV] at injection
0.31	0.31	= I [A] average
0.8	0.8	= ϵ_N [mm mrad]
2400	2400	= β_{\perp} [m] average
7.1	3.5	= b_o [cm] tube radius
6.0	6.0	= $f_o\tau$ [turns] growth time at injection

At feedback electrodes

5.3	2.6	= b [cm] tube radius
0.42	0.30	= σ [mm] at injection

Feedback System Description

Position data for each bunch would be picked up at the rate $f_B = 38$ MHz, stored digitally for one turn, and amplified to drive a number of kicker electrodes. Each kicker structure can be a stripline pair. The kicker power scales as b^2/β_{\perp} , making a location at large β_{\perp} preferred if b cannot be reduced to follow $\sqrt{\beta_{\perp}}$. I assume that b can be so reduced to simplify parameters, but a location at maximum β_{\perp} would be equivalent.

To just stabilize a coupled-bunch oscillation having amplitude A and growth $1/\tau$, the kickers must deliver a peak transverse voltage impulse of

$$V_{\perp} = \frac{2AE/e}{\beta_{\perp}f_o\tau} \quad (1)$$

The excursion A depends upon details of the injection process not now known. As a reference amplitude we shall use the rms beam size σ to find the following values:

$$V_{\perp} = \frac{(2)(4.2 \times 10^{-4})(10^{13})}{(2400)(6)} = 0.583 \text{ MV/turn, 2 tesla}$$

$$\frac{2(3.0 \times 10^{-4})(10^{13})}{(1200)(6)} = 0.833 \text{ MV/turn, 8 tesla} \quad (2)$$

To address all modes, the kickers must operate over a bandwidth of $1/2 f_B = 19$ MHz. The kicker electrode is most efficient at low frequency and the strong R-wall modes are at low frequency, therefore choose the band ~ 20 Hz to 19 MHz. Maximum kicker length is one half the bunch spacing of 8 meters and its stripline impedance may be 50 ohm. Calculate the kicker shunt impedances using

$$R_{\perp} T^3 = 2 Z_L \left(\frac{\sin kl}{k b} \right)^2 \quad (3)$$

to find per kicker unit

	B	2	8	tesla
$RT^2 @$	$f = 0$	0.57	2.37	mΩ
	$f = 23 \text{ MHz}$	0.12	0.48	mΩ

Choosing $N=12$ such units at 2 tesla and 8 units at 8 tesla, we find using

$$P = \frac{1}{2} \frac{(V_{\perp})^2}{NR_{\perp} T^2} \quad (4)$$

the total power for an amplitude of one σ :

	B	2	8	tesla
N		12	8	units
P		24.9	18.3	kW
P/N		2.1	2.3	kW/unit

We must remember that although these modest power levels are for the most unstable ($f_0 \tau = 6$) modes, the amplitude allowed was only one σ . Injected beam may have larger excursions. Only a portion of these injected motions will be rapidly growing coupled bunch modes. A power level can be determined that will damp the total excursions before the growing component becomes uncontrollable. For this technique, the gain is set as needed to stabilize the fastest-growing modes. Then the power output is allowed to respond to that gain value up to and limited at the level needed to bring injection errors into control. This avoids excess power that would be called for by linear

response to large excursions of a few injected bunches. This saves power most if only a small fraction of the total charge is injected and that is damped before the next batch.

Noise and Diffusion

We certainly want the feedback to damp coherent motions to smaller than the beam size σ , but more demanding is the requirement that diffusion from coherent motion to emittance be at a tolerable rate. For a very simple model of the complex diffusion process, we could assume that it obeys the relation

$$\frac{d\sigma^2}{dt} = DA^2 \quad (5)$$

in which A is the amplitude of coherent motion. A value for D used at the Workshop was $f_0/100$. The growth time for σ is then given by

$$T = \frac{100}{f_0} \frac{\sigma^2}{A^2} . \quad (6)$$

We assume that T is long compared to the time to damp motions down to a steady amplitude A.

The damping action of feedback with gain G per turn is

$$\frac{dx}{dt} = - f_0 G x . \quad (7)$$

Averaged over oscillations and in terms of A^2 this is

$$\frac{dA^2}{dt} = - f_0 G A^2 . \quad (8)$$

Opposing this are growth from electronic noise, coupled-bunch instabilities, and disturbances from the fields and the positions of magnets. Adding these, we have

$$\frac{dA^2}{dt} = - f_0 G A^2 + \frac{1}{2} f_0 G A^2 \langle x_N^2 \rangle + \frac{2}{\tau} A^2 + M . \quad (9)$$

Here x_N is the rms electronic noise at the pickup expressed as beam position, τ is the coupled-bunch growth time, and M is the rate of growth of A^2 from other sources. To use this simplified relation, we must assume that noises are random, that all modes have the same growth rate, etc. And M is just there as a reminder of how those disturbances enter.

At steady state, $dA^2/dt = 0$ and the amplitude is given by

$$A^2 = \frac{\frac{1}{2} f_0 G^2 \langle X_N^2 \rangle + M}{f_0 G - 2/\tau} . \quad (10)$$

We see that high feedback gain will reduce the contribution of M but for overall minimum A there is an optimum value of G . G cannot be less than $2/f_0\tau$ for the most unstable mode. To obtain some numerical results I shall use the gain $G = 4/f_0\tau = 2/3$, giving

$$A^2 < \frac{2}{3} \langle X_N^2 \rangle + 3M/f_0 . \quad (11)$$

A more detailed modal analysis supports the use of the "<" symbol here.

An estimate of the electronic noise can be made, in this case for a single stripline-pair of length $\lambda/4$ and an amplifier with noise figure 1.5 dB. Input noise in the frequency band $W = 19$ MHz will be

$$P'W = kT \cdot 10^{NF/10} W = (0.41 \times 10^{-20}) 10^{0.15} (19 \times 10^6) = 1.1 \times 10^{-13} \text{ watt} \quad (12)$$

The signal power from the pickup for excursion x is

$$P = Z_L (I x/2b)^2 . \quad (13)$$

Using this pickup gain we can find the equivalent input noise and emittance lifetime as influenced by this noise alone:

B	2	8	tesla
P	1.5×2	6.4×2	KW
x_N	8.6	4.1	nanometer
T	3.3	1.8	10^4 hour

This weak effect on emittance lifetime suggests that other noise sources such as magnetic noise and digital least count will dominate. Large dynamic range and fast data rate are required for the feedback. It may be necessary and practical to switch to a higher sensitivity immediately after the injection disturbances have been damped in order to have digital least count near 10^{-7} meter.

Summary

Practical transverse feedback systems can be provided if the coupled-bunch growth rates from resistive-wall impedance is limited in magnitude by proper design of the beam tube. Both allowed aperture and materials of the magnet bore tubes will be

constrained. Linearity of feedback response is not required above some oscillation amplitude smaller than initial beam excursions but determined by the details of beam injection. The product of charge times transverse error in an injected batch is important. Electronic noise can be negligible compared to feedback digital least count and disturbances delivered to the beam through the magnets. The effects of these latter noises on the growth of emittance need to be evaluated in the presence of the feedback systems.

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